

Life Qualification of Hall Thrusters By Analysis and Test

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High power Hall thrusters under development for deep space robotic and human exploration missions have demanding lifetime and operational requirements that make thruster life qualification challenging. The required burn times make it infeasible to conduct multiple tests with durations exceeding the life requirement, and complex wearout phenomena and the need for power throttling during missions complicate analyses and testing. The traditional qualification approach, a single life test that typically demonstrates 50 to 100% margin on the required lifetime, does not provide enough information to demonstrate low failure risk. It is a weak source of statistical information about the location of the peak in the failure probability distribution and provides no information on the width of the distribution. Testing does provide information that can be used to validate physics-based models of failure processes, however, and the combination can be used to assess mission risk. Validated, conservative, deterministic analysis can be used to demonstrate that most failure processes have such large margins that more detailed analysis is unnecessary. For a subset of the failure modes a more detailed probabilistic analysis is required. Pole erosion in a 12.5 kW Hall thruster is used as a detailed example of this qualification process.

I. Introduction

Solar electric propulsion (SEP) is a key technology for future human and robotic exploration missions and is now an integral part of NASA's vision for expanding human presence beyond low earth orbit. The high specific impulse of electric thrusters enables order of magnitude reductions in the required propellant mass, but at the price of burn times on the order of tens of thousands of hours.

NASA has launched two missions using electric propulsion for primary propulsion: Deep Space 1 (DS1) and Dawn. Deep Space 1 was an experimental spacecraft designed to test twelve new technologies, one of which was the ion propulsion system.¹ The criterion for successful demonstration of the ion propulsion technology was a total in-flight operating time of only 200 hours, although the thruster was actually operated for 16,265 hours.² The ion propulsion technology for DS1 was developed by the NASA Solar electric propulsion Technology Application Readiness (NSTAR) project,³ The objectives of this project included the demonstration of an operational thruster lifetime that would be useful for near-term, deep-space science missions. Consequently, a total of over 42,000 hours of ground-based thruster testing was performed under the NSTAR project. At the time DS1 was launched a functional-model thruster had been life tested for 8,200 hours⁴ and the DS1 flight-spares thruster was approximately 500 hours into what eventually became a test of over 30,000 hours.⁵

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The Dawn mission, designed to rendezvous with the main belt asteroid Vesta and the dwarf planet Ceres, was selected largely because of the success of the DS1 mission. The ion propulsion system for the Dawn mission⁶ employs three NSTAR thrusters with only one operating at a time. Two were required to process the propellant load and the third was included as a spare for single fault tolerance, although operationally thrusting has been split over all three thrusters. The Dawn project is nearing the end of its mission, having mapped both Vesta and Ceres in great detail. The three ion engines have accumulated 9468, 22251, and 19141 hours of operation over power levels per thruster ranging from 0.5 to 2.3 kW and have processed a total of 408 kg of xenon.

Since 2012 the NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL) have worked jointly to mature Hall thruster technology for a 40-50 kW system to support human exploration missions.⁷ This work has been supported primarily by the Space Technology Mission Directorate under the SEP Technology Demonstration Mission (SEP TDM) project with the goal of providing flight hardware for the first user of a high power electric propulsion system.^{8,9} The Asteroid Robotic Redirect Mission (ARRM), an ambitious mission concept that would have been enabled by high power SEP, was the intended target application until it was cancelled early in 2017.¹⁰ Work with the ARRM project helped shape the requirements for the system though, and a potential new user for a system similar to that envisioned for ARRM is the Power and Propulsion Element, a module providing propulsion for the proposed Lunar Orbital Platform-Gateway. This vehicle, which would also include a crewed habitat, is being considered for operation in lunar orbit to help develop capabilities for future human Mars missions.¹¹

The technology program has focused on the development of a thruster and power processing unit (PPU) for a 13.3 kW string. Three of these strings (plus a spare string) would form a 40 kW system. The Hall Effect Rocket with Magnetic Shielding (HERMeS), one product of the joint GRC-JPL development, incorporates a number of Hall thruster innovations developed over the last two decades.¹² Three technology development units (TDUs) like the one pictured in Fig. 1 were built for performance, environmental, and wear tests, as well as focused risk reduction tests. The TDUs have demonstrated operation at discharge voltages ranging from 300 to 800 V and discharge currents from 6 to 31.2 A. This corresponds to power levels up to 12.5 kW, thrust levels as high as 680 mN, and specific impulses up to 3000 s.¹³

The Advanced Electric Propulsion System (AEPS), which is being developed by Aerojet Rocketdyne as prime and VACCO and ZIN Technologies as sub-contractors under a competitively-awarded contract, includes design and testing of engineering development units (EDUs) based on NASA's HERMeS thruster and PPU development and a xenon feed system.¹⁴ The performance requirements for the AEPS are based on a subset of the throttling envelope with voltages ranging from 300 to 600 V and a fixed discharge current of 20.8 A. The lifetime requirement is 23,000 hours, which corresponds to a xenon throughput requirement of 1770 kg per thruster and a total throughput capability of over 5300 kg for the 40 kW system. The advanced system development is a coordinated activity with an integrated NASA/industry team. NASA is providing support to Aerojet Rocketdyne in several areas, particularly testing, risk reduction and life qualification.

The target missions for the AEPS have very high operating life and throughput requirements, which makes thruster qualification a significant challenge. The program incorporates several wear tests, including a planned life test of 23,000 hours (100% of the life requirement), but does not have the resources to perform multiple tests with durations exceeding the requirement. Given these limitations, the reliability of the thruster cannot be established by statistical analysis of life test data alone. The need to throttle the thruster over power profiles that have not yet been defined for future flight applications further complicates



Figure 1. The HERMeS 12.5 kW Hall thruster.

the qualification effort. To address these challenges the project is using a combination of wear testing and modeling of critical failure modes. The objective of the thruster design and lifetime qualification is to identify all potential failure modes, determine which can be managed by conventional conservative design and margin testing, eliminate wearout failure modes where possible, and obtain sufficient information through testing and analysis to demonstrate low risk for the critical failure modes.

In this paper we outline the approach traditionally followed for qualification of electric thrusters and discuss why that approach is problematic for deep space electric propulsion systems, then describe the alternative method for life qualification by a combination of testing and modeling. Examples from the SEP TDM Hall thruster development program are used to illustrate the life qualification methodology.

II. The Traditional Approach to Life Qualification

Ideally, the reliability of electric propulsion systems would be established by testing a large number of thrusters to failure, as shown in Fig. 2. These data could then be used to estimate the parameters describing the failure probability distribution. Because of the long burn times required for low thrust missions, this method is not feasible. Electric thrusters have typically been qualified for life by testing a single thruster for the required duration plus some margin. This strategy is reviewed in this section.

A. An Overview of Industry Practice

Commercial industry uses electric propulsion on a scale that dwarfs deep-space applications and this disparity is expected to increase significantly in the future as more and more commercial satellites transition to electric thrusters. Current industry practices for the life qualification of electric thrusters are therefore highly relevant.

Commercial applications of electric propulsion include north-south and east-west station-keeping, attitude control, momentum dumping, de-orbit, and orbit raising. Typical ΔV requirements are approximately 50 m/s per year for stationkeeping of geosynchronous communications satellites plus additional ΔV for a portion of the orbit insertion with the EP system. The systems that have been flight qualified for use on western spacecraft include hydrazine resistojets and arcjets, the Xenon Ion Propulsion System (XIPS) 13-cm and 25-cm ion thrusters, the SPT-100 Hall thruster, and the XR-5 Hall thruster (previously called the BPT-4000). Higher power engines such as the XIPS 25-cm and XR-5 thrusters are designed for two operating point—a high power mode for orbit-raising and a lower power mode for station-keeping and momentum dumping. Extensive life-testing of these thrusters has been performed.^{15,16} The XIPS 13-cm and 25-cm thrusters have accumulated 37,204 hours and 20,565 hours of ground test experience, respectively.¹⁵

This section briefly summarizes the results of a survey of a number of propulsion system providers and spacecraft integrators around the world. All commercial spacecraft customers require single-fault-tolerant systems which can accommodate a thruster failure on day zero, a requirement that is met by including redundant thruster strings. There are a variety of internal guidelines and standards as well as customer-imposed requirements on thruster life qualification. None of these standards were developed specifically for electric propulsion, and all apparently stem from one of two sources. The majority appear to be based on an early Comsat requirement that thrusters be qualified for life by test with durations equal to 1.5 times the required mission life. Some customers specify a margin of 30% instead of 50% (a test of 1.3 times the mission life). These margins are generally applied to the worst case circumstance, assuming a thruster failure on day

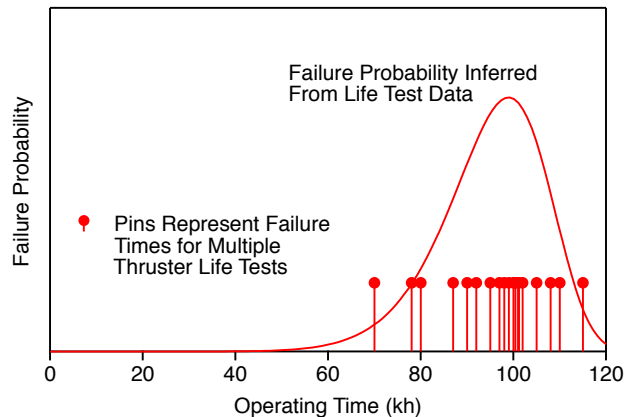


Figure 2. The ideal approach to life qualification.

zero, and may be calculated in terms of thruster operating time or total impulse. The same requirement is generally applied to the number of required thruster on-off cycles. Military customers require compliance with MIL-STD-1540E, which specifies a test of 2 times the mission life. If this margin is applied to the nominal mission life and cycles (assuming no thruster failures) it is less demanding than 1.5 times the worst case mission life in terms of operating time, but generally more demanding in terms of cycles. An additional margin of 15 to 30% is applied to this in some cases.

All industrial standards specify that life qualification tests are to be performed with qualification units identical to the flight hardware. This requirement is designed to address experiences with engineering model or breadboard hardware that exhibited differences from later production hardware. There is a general consensus that thrusters should be tested with the most mature power processing hardware available (flight-like if possible) to capture any influence of power supply characteristics on wear.

Commercial satellite customers require that spacecraft meet minimum mission success levels, and subsystem suppliers are responsible for a quantitative subsystem reliability assessment. This is generally accomplished using standard methods such as MIL-HDBK-217. It is not clear how these methods apply to electric thrusters subject to complex wearout failure modes, however.

There is general recognition that a single life test does not guarantee thruster reliability in any statistically significant sense. This issue is addressed in two ways. The first is the use of margins (the 30 to 50% margin in test duration, for instance) to capture the uncertainties in unit-to-unit variability or intrinsic variability in the wearout processes. The second approach is to perform additional testing for critical failure modes. This is often done at the component level and in some cases accelerated test methods have been employed.

Commercial applications generally demand less throttling than planetary missions. Thrusters are designed for a fixed operating point (the SPT-100 and XIPS 13-cm thrusters, for instance) or for a restricted set of points—typically one for orbit-raising and one for station-keeping (the XIPS 25-cm and XR-5 thrusters, for example). Arcjets are required to throttle because of propellant tank blowdown, and the profile varies from application to application. For thrusters such as the XR-5 and XIPS 25-cm the original qualification tests were conducted in two phases, one at each operating point, and the 1.5X requirement on duration or impulse and cycles is followed for each phase. Arcjets were qualified with a test which represented a nominal blowdown profile with a mix of short and long cycles designed to bracket the anticipated range. Additional tests were performed to extend the life and to cover different duty cycles or thruster configurations. In some cases with only small changes in throttling levels, the systems were qualified by analysis or similarity, without retesting. There is no generally accepted standard for qualifying thrusters for a large range of throttle levels, but the consensus is that testing should envelope the expected range and be designed to assess the risk due to critical failure modes.

Physics-based models of known failure mechanisms are currently used primarily in the development phase to improve the design and increase confidence prior to the qualification test. For example, Aerojet developed a model of insulator wear and performed a number of wear characterization tests during development of the XR-5. Models are also used to identify the worst case operating conditions to help design the qualification test. More detailed modeling and tests may be triggered by an unexpected failure in a qualification test. For instance, L3 performed a very detailed characterization of cathode heater failure mechanisms followed by extensive qualification testing at the component level after a discharge cathode heater anomaly was observed in the XIPS 25-cm life test.¹⁷ In some cases, failure models are used to justify minor design changes without requalification. These models are validated with test data, which is sometimes obtained in component tests and using accelerated test methods. Although accelerated testing is widely accepted for other subsystems, the only accelerated test method currently used in thruster qualification is to increase the duty cycle by shortening the off-time in cycled tests. This is considered representative of actual operation as long as the proper thermal conditions at start-up are reproduced. Accelerated testing is being used increasingly to study critical failure modes in various thruster components.

B. Challenges in Life Qualification for Electric Thrusters

Current industry practice is based on standards that govern chemical thrusters. Fundamental differences in chemical and electric propulsion technologies, however, limit the usefulness of this approach. These

differences include much longer required operating times, continuous pressure from mission planners to push thruster operation to the lifetime limits, significantly different wear mechanisms, and operation over a broad throttle range. These issues are discussed in this section.

1. Long Life Requirements Make Extensive Testing infeasible

Typical lifetime requirements for a chemical thruster on a deep space mission may be several hours; however typical lifetime requirements for an electric thruster on the same mission may be several years. This fact makes lifetime testing and life qualification much more difficult for electric thrusters. For example, the development of the ion propulsion system for the Dawn mission⁶ relied heavily on the 30,352 hour weartest of the ion thruster,⁵ although it proved to be very difficult to perform and to keep funded for the five years that it ran. Conducting long duration tests within the timescale of typical spacecraft development cycles for near-term missions is extremely challenging. The Jupiter Icy Moons Orbiter (JIMO) mission, although ultimately cancelled for budgetary reasons, provides an extreme example of the challenges posed by planetary mission applications. JIMO was a proposed mission to explore Callisto, Ganymede and Europa using nuclear electric propulsion technologies under development as part of the Prometheus Project. The nuclear reactor-powered spacecraft proposed for this mission would have used six ion thrusters operating at up to 30 kWe each for a 5 to 8 year interplanetary cruise phase, followed by a 4 to 6 year science observation phase involving orbit transfers between the three moons. The high ΔV of this mission (50 km/s) would have placed extraordinary demands on the propulsion system. The initial estimate of the required thruster life was 83,000 hours. The standard approach of qualifying the thruster with a single test of 1.5 times this duration, assuming a test duty cycle of 75%, would have necessitated an inconceivable 19 years of testing. In this case, with no chemical propulsion alternatives and no realistic hope of qualification by test, the project management accepted a different risk management strategy for the electric propulsion system involving life qualification by a combination of long duration tests (as much as was realistically feasible) combined with physics-based models of the critical wearout failure modes benchmarked by extensive and highly instrumented component and thruster-level tests. The AEPS program is planning a test with 23,000 hours of operation which will last on the order of 3.5 years, and it will be a challenge to complete this before the first use on a NASA mission.

2. High Reliability Cannot be Established by Limited Testing Alone

The current approach, testing a single thruster for 150% of the required propellant throughput over a throttle profile that is necessarily different from that ultimately used in a mission, is inadequate to determine the wearout failure risk. This approach is illustrated in Fig. 3 where a life test of duration t_{LT} was suspended prior to thruster failure. The “qualified” life is given by $t_q = t_{LT}/(1 + M)$. The traditional 50% margin is obtained for $M = 0.5$. The problem with this approach is that the location and width of the actual failure distribution is unknown based on the information from the life test alone. It is normally assumed that the failure distribution is located as shown in this figure, but this may not be the case.

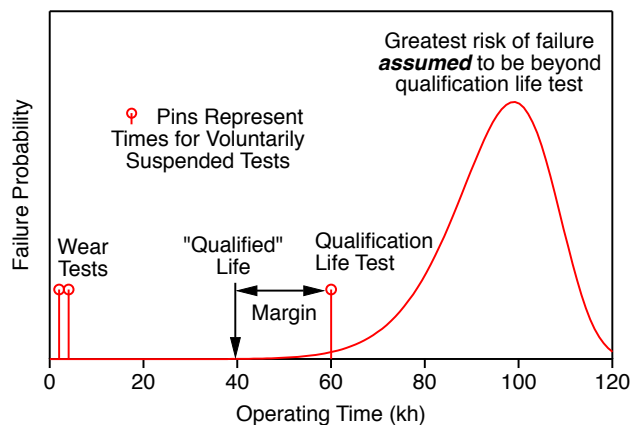


Figure 3. The traditional approach to life qualification.

For example, the SERT II thrusters were subjected to substantial development and life testing prior to the launch of the flight experiment 1970.¹⁸ This testing included 20,000 hours of component testing, three tests of approximately 1200 hours each, and two long duration tests of 5169 hours (Test “T”)¹⁹ and 6743 hours (Test “M”). The mission objective for the flight experiment was six months (4380 hours) of operation per thruster. Therefore, the life Test “M” demonstrated 154% of the mission requirement. Two identical ion thrusters were flown on the SERT II spacecraft

and neither thruster met the required operating time in flight. Thrusters 1 and 2 were operated for 3781 hours and 2011 hours, respectively, before developing unclearable grid shorts. The root cause of the failures, sputter erosion of the accelerator grid near the neutralizer cathode, was identified prior to flight, but the mitigation approach and subsequent life testing proved to be insufficient to protect against this failure. This experience highlights a critical lesson. While the failure mode was known, the details of how the wearout failure actually behaved were not. In his excellent summary of the history of the SERT II flight experiment, Kerslake¹⁸ states that “The solution of adding a local double thickness to the accelerator grid provided sufficient assumed life for the grid. The grid short problem caused by web fragments was not anticipated” The subsequent failure investigation identified the critical behavior also summarized by Kerslake, “As the erosion groove developed, web-like fragments of the grid were produced, broke off, and in ground tests were later found at the bottom of the vacuum tank. In space where the ion thrusters were in near-zero gravity, the web fragments (it was believed) would not fall away from the grids but would be electrostatically attracted and spot-welded between the grids.” This highlights a second critical lesson, that life tests must be examined critically for each failure mode to identify whether or not the ground test is conservative for that failure mode relative to flight.

Relying on one test of 1.5 times the mission duration is equivalent to assuming that the failure probability distribution for the critical failure mode is narrow (i.e. little variation in the time-to-failure from thruster to thruster) and that the required mission life is far from the location of the failure distribution (defined by some parameter such as the time of the peak failure probability or mean time-to-failure). There are two problems with this approach in a quantitative sense. First, test data alone is a weak source of information about the location of the failure distribution. Second, a single test provides no information at all about the width of the failure distribution. For example, assume that the critical failure mode follows a Weibull distribution like that shown in Fig. 2 or 3,

$$P_f = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{(\beta-1)} \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right] \quad (1)$$

where P_f is the failure probability, t is operating time, β is the shape parameter and is related to the width of the distribution (a larger β corresponds to a narrower distribution), and η is the location parameter (equal to the peak in the probability distribution for large β). The Weibull distribution often provides a better description of wearout failure probability than other candidates, such as exponential, normal, or extreme value distributions²⁰

For N non-failure tests (i.e. tests which are terminated before the thruster actually fails) of equal duration T the lower bound estimate of η with a confidence C is²¹

$$\eta = T \left[- \frac{\ln(1-C)}{N} \right]^{(-1/\beta)} \quad (2)$$

Assume a relatively narrow failure distribution of $\beta = 10$, as shown in Fig. 4. It is important to note that there is no reason to assume a narrow or broad distribution a priori and no information from a single test to indicate that it is narrow or broad, but we pick this value as an example. The best quantitative estimate of η with a confidence level of 95% from the single 30,352 hour NSTAR thruster wear test is 27,200 hours. It may seem surprising that the estimated peak failure probability occurs at a time somewhat less than that achieved in the test, but this just reflects the fact that, in the absence of any other data, one cannot conclude much with high confidence other than that a thruster will last about as long as it did in the single test.

If the thruster looks good at the end of the test, it is tempting to conclude that it actually has much more life capability. It is likely true that the estimate of the failure distribution location parameter η from a single non-failure test is conservative, but the observation of relatively little engine wear does not by itself provide any better quantitative estimate of η .

Further, the conclusion that an observation of little engine wear implies high reliability is equivalent to assuming that the duration of that test corresponds to a point far down on the left-hand tail of the failure probability distribution. However, neither the location parameter η nor the width parameter β that actually determine whether the test time is low on the left-hand tail can be quantitatively obtained from the data from the single test. Three examples illustrate the danger in making this assumption.

First, consider a near-threshold sputter erosion process such as wear of the keeper electrode in the NSTAR thruster discharge cathode assembly, which is driven by the potential of the keeper, the amplitude of potential oscillations in the discharge plasma, and the double ion content. Because the sputter yield increases so rapidly with energy near the threshold, the erosion rate is very sensitive to small variations in energy. One life test in which the keeper voltage is at the high end of the allowed range or in which the amplitude of plasma potential fluctuations is at the low end of the expected range might exhibit relatively little erosion because the potential differences determining the ion energies are low. One might conclude from this test that the demonstrated operating time is associated with low failure risk. However, in a subsequent test of the same duration in which the keeper voltage is at the low end of the tolerances, the plasma potential fluctuation amplitude is somewhat higher, or the double ion content is higher, the erosion rate could be dramatically higher because of the sensitivity of the sputter yield to energy, perhaps leading to failure. The erosion observed in the first test is misleading; the level of erosion observed in a single test is not a reliable indicator of failure probability. The risk is driven by extreme sensitivity to what may be considered to be normal variations in engine operating parameters.

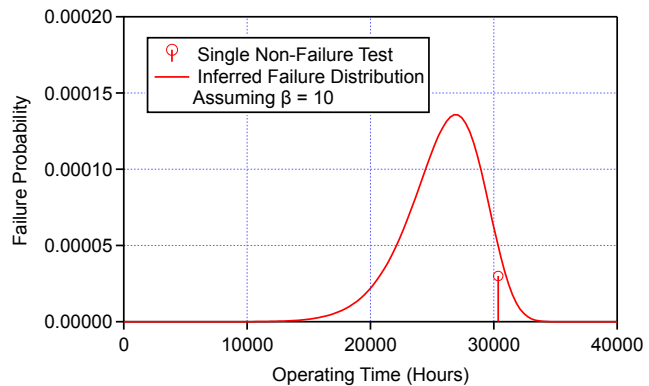


Figure 4. Example Weibull distribution inferred from the NSTAR life test for an assumed shape parameter $\beta = 10$.

Second, the experience with grid erosion in the SERT II program is a graphic illustration of how successful tests may not represent low failure risk. In this case the ground testing environment differed from that in space in an important way, and sensitivity to this parameter led to different behavior. The two successful ground tests representing 118% and 154% of the mission requirement were followed by two failures in orbit at times less than the requirement. Erosion that appeared to be acceptable in the ground tests was not a true indicator of failure risk, which in this case was driven by variability in the environment (1-g ground tests vs. near zero-g space environment).

Finally, the amount of wear observed at the end of a test with a throttling profile may be very sensitive to the particular profile chosen. For example, if the thruster used in the 30,352 hour ELT had processed the same amount of propellant but not accumulated significant operating time at low power, neutralizer orifice clogging would not have been observed. The same neutralizer design which experienced relatively little degradation in this test may have failed in a subsequent test or mission application if it involved extended operation at low power. Similarly, a test conducted mostly at an intermediate power level might not exhibit much grid erosion, but a test with the same xenon throughput accumulated at a mix of low and high power levels near the perveance limit would experience much greater grid erosion. These two extremes show that it is even difficult to design a conservative test by operating under the worst case conditions.

Without understanding the physics of failure processes and the sensitivity to throttled conditions, we cannot rule out large variability due to different throttle profiles, even with similar throughput values.

These three examples represent different types of intrinsic variability in the failure behavior, and therefore the probability distribution over time. The first illustrated extreme sensitivity to variable engine operating

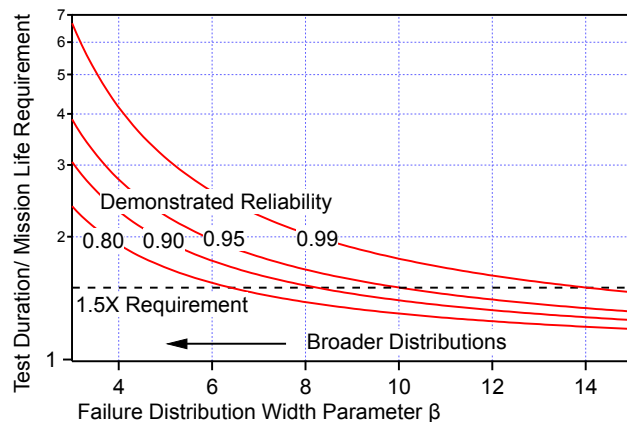


Figure 5. Narrow Weibull distributions ($\beta \geq 14$) are necessary for a single test of 150% of the mission requirement to demonstrate a high reliability (≥ 0.99) with high confidence (95%).

parameters, the second demonstrated variability in the thruster environment, and the third showed variability introduced by different throttling profiles. The greater the variability, i.e. the wider the failure distribution, the longer the life test must be in order to demonstrate high reliability at the desired mission life. As Fig. 5 shows, the typical test duration of 1.5 times the mission life demonstrates a reliability of 0.99 at 95% confidence only if the β parameter is 14 or greater, which corresponds to a very narrow distribution for the failure probability. Broader distributions, or greater variability, result in lower and lower demonstrated reliability with a single non-failure life test of 1.5 times the mission life. The problem, of course, is that the life test alone does not provide the information required to determine whether the failure distribution is broad or narrow. With limited non-failure test data it is impossible to distinguish between high reliability components and problem components that have just not failed yet. So, for spacecraft components such as electric thrusters that have very long life requirements, it is not feasible to conduct many long duration tests. The limited number of tests provides only a very poor estimate of the location of the failure distribution, and little or no information on the width of the failure distribution. This results in an inability to establish high reliability by testing alone.

3. Requirements Creep Tends to Erode Margins

Another key difficulty is that most deep-space science missions benefit from longer life thrusters. The simplest, least expensive electric propulsion systems are those that do not need “extra” thrusters added just to be able to process the required total propellant for the mission. The Dawn IPS is an example of the case where an extra thruster had to be added because of the limited propellant throughput capability of the NSTAR thruster. Each NSTAR thruster would have had to be capable of processing approximately 400 kg of xenon with a low risk of wearout failure in order to have deleted the third thruster and still meet the single-fault-tolerance requirement.

Deep-space science missions that will use electric propulsion are those characterized by high post-launch ΔV requirements (typically greater than 8 km/s) from the on-board propulsion system. If the post-launch ΔV requirement is not at least approximately this high, then the mission will almost certainly be done using chemical propulsion. Electric propulsion systems which are the least expensive and the simplest to integrate and test are those with the fewest thrusters. This combination of high ΔV with the fewest number of thrusters tends to push electric propulsion system designs to the limits of the thruster’s propellant throughput capability. Changes that occur during the spacecraft development are likely to aggravate this situation as illustrated by the Dawn mission.

Dawn was one of three missions selected in the late fall of the year 2000 from the Step 1 Discovery proposals.²² Prior to this, in the spring of 2000 a special review board from across NASA was convened to assess the operational life capability of the NSTAR ion thruster. At this review a detailed combination of analyses and test data were presented to support a recommendation that the NSTAR ion thruster could be used up to a total propellant throughput of 130 kg with a low risk of wearout failure provided the average input power to the thruster was less than 2.1 kW (the maximum thruster input power is 2.3 kW). At the time of this review the DS1 flight-spare thruster had been operated in the extended life test (ELT) for 9,400 hours and had processed 80 kg of xenon. The review board agreed with the recommendation that the NSTAR thruster could be assumed in Discovery proposals to have a low risk of wearout after processing 130 kg of xenon, but made the strong recommendation that the ongoing life test be extended until the thruster failed. The Dawn proposal stayed within the 130-kg throughput limit per thruster. By the time the Step 1 proposal selections were made the life test of the DS1 flight-spare thruster had reached 14,000 hours, the

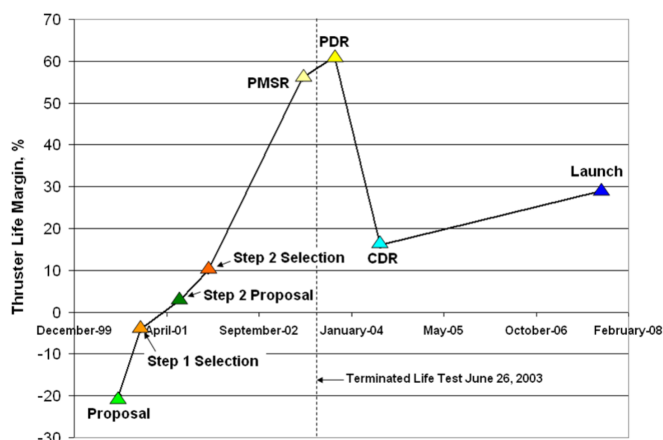


Figure 6. Life margin demonstrated by test during the Dawn mission development.

thruster had processed approximately 125 kg of xenon, and all electrical and diagnostic measurements indicated that the thruster was in good health. As the ELT progressed, the thruster life margin demonstrated by test increased up to the Project PDR as shown in Fig. 6. The Step 2 Discovery proposals were submitted in the summer of 2001 and Dawn was one of two missions selected for flight implementation in December of that year. At this time the thruster in the ongoing ELT had passed 20,000 hours, had processed 160 kg of xenon, and still appeared to be in good health.

During the spacecraft development phase, the criteria for full mission success were modified. These modifications had a direct effect on the ion propulsion system (IPS). The change in mission success criteria now required that the ion propulsion system be single-fault-tolerant through the completion of the orbital operations at Ceres. Prior to this the IPS had to be single-fault-tolerant through only the completion of the Vesta science phase of the mission. According to the trajectory analyses at the time, to complete the Ceres operations required the IPS to process a total of 400 kg of xenon. The Dawn ion propulsion system included three NSTAR ion thrusters and the single-fault-tolerant requirement meant that the system had to be capable of processing this xenon through just two ion thrusters assuming the third thruster failed right at the beginning of the mission. This change consumed most of the margin in life demonstrated by test, as shown in Fig. 6.

In short, deep-space science missions are likely to require electric propulsion systems in which the thrusters must be used to the limit of their operational life capability. The life qualification effort must therefore determine the maximum propellant load that the thruster can process over the mission throttle profile with a low risk of wearout failure.

III. Life Qualification by Analysis and Test

An alternative to reliability demonstration by test alone, with all the limitations noted above, is to use a combination of testing, modeling, and analysis to provide confidence that a design has adequate lifetime capability. In this case, the focus is on individual failure modes and the information used to assess the failure risk comes from both experimental data and modeling. This approach relies on diligence in identifying all critical failure modes. Potential failure modes are classified and screened, and the vast majority can generally be handled by standard conservative design methods, margin testing, and quality assurance screening. A small fraction of wearout failure modes typically remain as potential life limiters. The objective of the approach is ultimately to estimate the location and shape (width) parameters of the failure distributions associated with these critical failure modes and demonstrate adequate life margins.

A. The Role of Testing

Although the limited life testing typically feasible in electric thruster development programs is a weak source of statistical information about the location and width of the failure distribution, it is a rich source of information for identifying failure modes, determining the failure mechanisms, characterizing failure mode behavior during the approach to failure, guiding the development of models, specifying model input parameters, validating failure models, and characterizing uncertainties in models and model input parameters. These are critical steps in understanding how engines fail, which failure modes are important, and how much uncertainty there is in a predicted engine lifetime. An important question is how many thrusters should be tested and for how long.

If testing alone is used to determine reliability, a quantitative estimate of the number of test articles and test duration required for a given reliability level R and mission life requirement t_m can be developed in answer to this question. Assuming the failure probability can be approximated by a Weibull distribution (Eqn. 1), the reliability for operating time t is given by

$$R(t) = \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right]. \quad (3)$$

The lower C% confidence limit for the Weibull shape parameter β inferred from N tests of duration T assuming none of them fail is given by Eqn. 2. Combining these relations yields the test duration in multiples

of the required mission life T/t_m as a function of the number of thrusters tested and the width of the failure distribution β . This is plotted in Fig. 7 for a reliability of 99% at 95% confidence for a range of β values. This plot demonstrates that for failure modes with small β values (broader failure distributions) many tests with durations considerably longer than the mission requirement are needed to establish high reliability. This is the fundamental problem with relying on testing alone—it is unlikely that a deep space mission which requires a lifetime of several tens of thousands of hours will have the time or resources to conduct more than one test with a duration approaching the lifetime requirement.

Because the burn times for liquid rocket engines are much shorter than those for electric thrusters, it is more feasible to conduct multiple life tests with durations exceeding the operational life requirement. In 2011 the JANNAP Liquid Propulsion Subcommittee Test Practices and Standards Panel published guidelines for liquid rocket engine testing.²³ They recommend tests of multiple engines to determine the variability from unit-to-unit and life test durations of 2–4 times the required life to demonstrate adequate margin against failure modes such as high cycle fatigue, which exhibits large scatter in time-to-failure. In contrast, they recommend only 20% margin in testing for ablative nozzle testing, based on experience which demonstrates that ablative nozzle erosion rates are less variable.

The electric propulsion community does not yet have sufficient test experience to make a similar determination about the intrinsic variability of most electric thruster failure modes. It may be possible, however, to assess the variability of some wearout processes with modeling and tests. For example, the physical mechanism for thruster wear is often erosion due to sputtering, and a focused characterization of this process for a given failure mode could provide enough information to define the width parameter β . This characterization could be experimental, or it may employ properly validated models with Monte Carlo analysis to assess the variability in time-to-failure that results from variability in model input parameters. Then it would be possible to quantitatively define the required test duration and number of test articles to establish high reliability (although it may still not be feasible to conduct that level of testing). For example, a probabilistic analysis of electron backstreaming failure due to grid erosion at full power in the ion thrusters used in the Dawn mission²⁴ yielded the distribution of failures as a function of engine throughput at the time of failure shown in Fig. 8. This is a symmetric distribution (because the distributions used to describe uncertainty in the input parameters were symmetric), but it can be approximated by a Weibull distribution with a β of about 9. This is a fairly narrow distribution, but it would still require a successful single life test almost 99% as long as the mission requirement to demonstrate 99% reliability at 95% confidence by test.

This question is much harder to answer if the width of the failure distribution is not known. In the alternative approach, using a combination of limited testing and analysis, the wear testing must provide several critical pieces of information. First, wear testing (and related experience) must expose all important failure modes

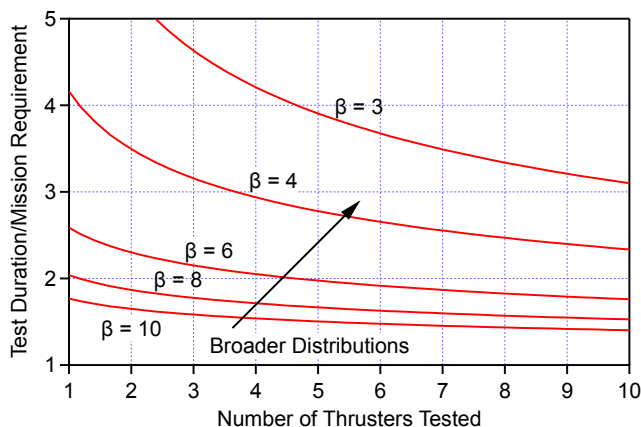


Figure 7. The length of testing required depends strongly on number of units tested and the width of the dominant failure mode. Curves represent 99% reliability at 95% confidence for a range of failure distribution widths.

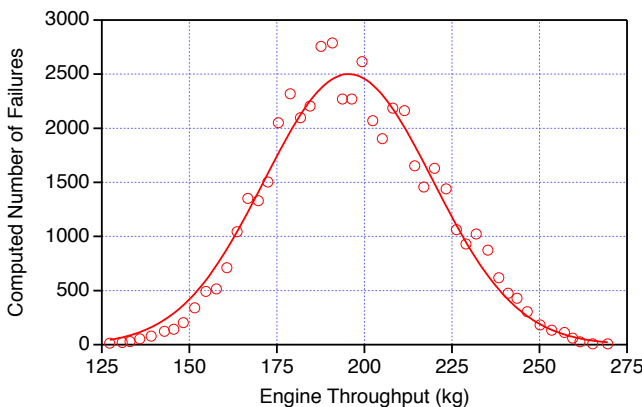


Figure 8. Number of engine failures observed as a function of throughput at the time of failure in a Monte Carlo simulation of the electron backstreaming failure mode for the Dawn ion thruster operated at full power.²⁴

so they can be analyzed. Second, it must reveal how wear processes evolve as the thruster approaches failure to ensure that models capture behavior that deviates from that experienced early in life. Ideally, a test to engine failure would be conducted to satisfy these requirements, although that may not be feasible. For a thruster with substantial development history (such as ion engines and Hall thrusters), we recommend a test of at least 100% of the mission requirement. Newer thruster technologies will require substantially more test experience to adequately characterize the important failure modes.

B. The Role of Modeling and Analysis

In this method, models and simulations validated by data are used to predict the time-to-failure. If the predicted time-to-failure is much greater than the mission life requirement and the uncertainties are relatively small, that particular failure mode may not be considered credible. For cases where the predicted time to failure is comparable to the mission life, techniques such as Monte Carlo analyses²¹ can then be used to quantitatively determine the distribution of predicted failure times associated with variation in input parameters. In Monte Carlo analyses like that shown in Fig. 8, a large number of simulations are conducted with input parameters sampled out of distributions which represent the uncertainty in those parameters, and the failure probability distribution is inferred from the predicted failure times. An important difference between statistical analysis of test data and the Monte Carlo simulation approach is how the spread of these distributions is interpreted. The spread in data is due to intrinsic variability (such as unit-to-unit dispersions, variability in materials properties, and inherent stochastic behavior of some failure modes such as crack propagation), experimental errors, and environmental effects. The distribution inferred from a sufficiently large sample of life tests would more accurately represent the parent distribution of failures. In contrast, the spread in predicted failure times based on modeling and simulation in a Monte Carlo analysis is due to the intrinsic variability of the parent population plus uncertainty in the values of the input parameters (which may be greater than the true variability). For example, the real variability in sputter yield at a given energy is likely very small, but the uncertainty in what that value is based on sputter yield measurements is typically quite large.²⁵ The distribution determined by analysis therefore represents our lack of knowledge about the failure process as well as the intrinsic variability.

As discussed above, testing alone is unlikely to demonstrate the required reliability. In contrast, modeling and analyses can provide a quantitative estimate of failure risk, incorporating both the spread in the actual failure distribution and our lack of knowledge about driving parameters and the physics of failure. This capability allows projects to select the correct margin to control failure risk. In this case, the key question is how much margin should be demonstrated by analysis if the life testing duration is only 100% or less of the required mission life.

The role of margins is to guard against several threats: variability, unexpected changes in environment, changes in requirements, and “unknown unknowns.” Because these threats are often unknown, it is difficult to define what margin is required to ensure low risk. This is related to the problem discussed in the previous section—it is not possible to establish testing requirements without knowing the width of the failure distribution. This knowledge comes about mostly through hard-won experience, but it’s not clear that we have enough experience with electric thrusters.

The traditional life qualification approach treats life limited by wearout failure modes as a quantity that can be margined, with margin demonstrated in a single wear test. This is a reasonable approach for event-consequent failure modes (those resulting from a single episode where a load exceeds a component’s capability). These generally involve well-understood failure processes with well-characterized failure distributions, and don’t require long duration tests to demonstrate margin. A life test is a very long single episode. This approach is inherently high-risk for wearout failures because experience is generally insufficient to know how broad the failure distribution is and how much margin must be applied, and being overly conservative might result in qualified lifetimes that are unacceptably short. A single wear test, particularly if voluntarily terminated, provides no information on the width of the distribution. It also provides no information on the margin at operating points and/or environments not tested (space vs. ground, for instance, or with variable input parameters).

To demonstrate margins in the context of life qualification, one must first determine the nominal time-to-failure by analysis and testing. For a Weibull distribution this can be defined as the location parameter η ,

which is near the peak in the failure probability curve. The margin is then defined as $M = (\eta - t_q)/t_q$, where t_q is the qualified lifetime (so $\eta = 1.5t_q$ represents a margin of 50%). The qualified life t_q is defined to give the required reliability (typically 0.99 to 0.9999, or a failure risk of 1/100 or 1/1000) at a given confidence level. The reliability as a function of the margin depends on the width of the failure distribution β (of course):

$$R(M) = \exp \left[- \left(\frac{1}{M+1} \right)^\beta \right]. \quad (4)$$

This relationship is plotted in Fig. 9 for a range of distribution widths. As expected, wider failure distributions (lower values of β) require more margin. Limited testing cannot provide an estimate of β (or an estimate of η , without an assumed value of β), so the margin is selected on the basis of physics-based modeling and analysis informed by testing. Demonstration by analysis that a thruster operated for a time t_q has a margin M for a particular critical failure mode guards against variability in the failure process (or uncertainty in the analysis of the process). Sensitivity analyses performed with models validated by testing can also be used to identify the biggest contributors to the lack of knowledge and guide investments in additional modeling or focused experiments to reduce the uncertainty and the required margin. The modeling and analysis are an attempt to make the unknown failure distribution known, but as noted above, there are other threats. A project may choose to levy additional margin requirements to guard against these unknown unknowns.

Properly validated models can also provide insight into operating conditions and environments that differ from those tested. For example, it is generally not feasible to test the exact throttle profile used in a mission or get wear data at all relevant throttle levels. However, testing can be used to characterize the failure mode drivers over a range of throttle levels. Models can then be used to determine the wear for a given throttle profile, as was done in the analysis of the Dawn ion propulsion system.²⁴ Ground testing generally involves some differences in the environment compared to operation in space.

Modeling and analysis can be used to assess the impact of design changes. Design changes are virtually inevitable, often as a result of the lessons learned during the final wear test. Such changes could invalidate the wear test if it were the only source of information. Validated models can be used to determine if the changes are benign or could affect engine wear and are a critical part of delta-qualification efforts.

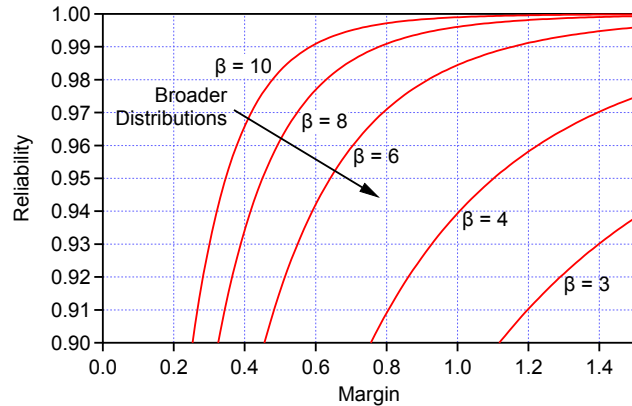


Figure 9. Reliability at qualified life t_q for various failure distribution width parameters β as a function of the margin.

C. Combined Approach for Life Qualification

The combined approach involves first identifying and classifying potential failure modes. Conservative design and margin testing can generally be employed for event-consequent failure modes, which are those due to a single event in which a load such as stress exceeds a capability such as strength (in contrast to wearout failure modes where damage is accumulated over a long period of operating time or cycles). Event consequent failure modes include structural failures due to launch loads and possibly conditions where temperatures exceed design limits, although in this case the coupling between temperature and wearout failure processes must be considered. Other events which can lead to random thruster failures such as design flaws, workmanship errors, materials flaws, and misuse can be managed with standard engineering practice.

The failure mode identification and characterization process should be a part of the design phase. The philosophy should be to design for life, which involves pushing wearout failures well beyond the required lifetime where possible. Examples of this approach include the application of magnetic shielding in Hall

thrusters, which was developed to eliminate discharge channel erosion, and sizing hollow cathode orifices to eliminate orifice erosion and recycle barium to prevent emitter failure. The thruster design can also incorporate features to minimize the risk of certain workmanship errors or misuse.

For the dominant wear out failure modes, a combination of analysis and structured tests and experiments are used to assess failure risk. This includes wear tests to identify failure modes and characterize failure drivers, models validated by experiment to understand failure processes and predict time to failure, tests and analyses to characterize variability in failure mode drivers and model uncertainties, and probabilistic methods to predict the uncertainty in the time to failure. These activities result in an assessment of whether the thruster can meet the mission life requirement with the required margin. The following sections describe the approach in more detail.

D. Identifying Failure Modes

Missing a critical failure mode renders this approach useless, so identifying potential failure modes is a key first step. There are many sources of information on potential failure modes. Experience from hundreds of thousands of hours of electric thruster testing shows that most important failure modes produce some signs early in testing. For example, inner front pole texturing by sputter erosion was observed in two 150 hour tests of the H6 Hall thruster.²⁶ This process was subsequently shown to be a critical wear process for magnetically shielded Hall thrusters.²⁷ Cathode keeper-to-cathode shorts were identified as a potential failure mode in the first 8200 hour test of the NSTAR ion thruster, and were then observed in longer duration tests of the NSTAR and NEXT thrusters.^{4,5,28} As noted above, differences in test and flight environments can impact wear rates. It is therefore important to understand and control for facility effects such as ambient pressure and carbon backsputter on performance and failure mode drivers.

Experience from other development programs is also important, including wear processes observed in previous thruster tests and in other related devices. For instance, the cathode used in the AEPS Hall thruster is similar in design to the space station plasma contactor and the NSTAR and NEXT discharge cathodes. Wear processes observed in those programs are being considered potential failure modes for the AEPS cathode. The technology base for processes such as welds and brazes and materials data can provide clues to potential thruster failure modes and engineering analyses such as structural and thermal modeling may point to potential problems.

Finally, there are structured approaches to failure mode identification such as Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA). FMEA is a bottoms-up approach that starts by identifying component functions and mechanisms that could lead to loss of function and then traces the impact of those failures on the assembly, subsystem, and system. FTA is a top-down approach that starts with possible system failure modes and traces them down to potential mechanisms in individual components. Both are important tools for documenting failure modes gleaned from test experience, materials and processes data, and modeling as well as brainstorming potential failure modes that have not yet been observed in testing.

E. Classifying Failure Modes

Figure 10 shows several possible classifications and corresponding control methods. The first categorization is by type of cause: event consequent or wearout. As discussed above, this is an important discriminator between failure modes that can often be dealt with by conservative design and margin testing and those that require more complex treatment. A second categorization divides failure modes by when the root cause of the failure process occurs. Failures can be inherent in the design, and we distinguish design flaws from poor material choices. Design analysis, materials testing, development tests, and ultimately qualification tests should screen out most improper designs. A sound design may be improperly manufactured. In this case we distinguish material flaws, workmanship errors, issues with processes as particular causes of failures. The standard quality assurance practices; including inspections, material testing and certifications, and acceptance tests; should be designed to detect and prevent manufacturing flaws. Finally, assuming a good design has been properly manufactured, it may still fail during use due to unexpected environments, wearout, misuse, or mishandling. The latter can generally be avoided with good design and engineering

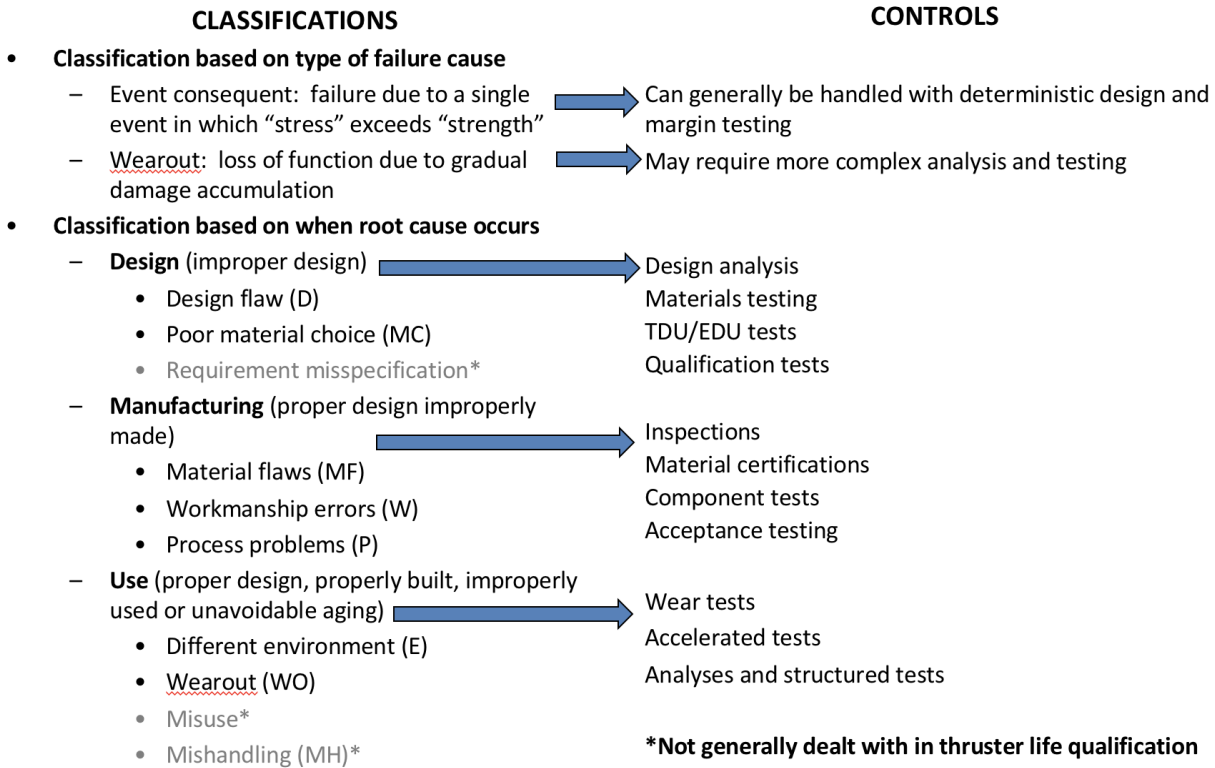


Figure 10. Failure mode classification and corresponding controls.

controls. Careful consideration of environments during the design and test phase is critical. In addition to potentially important differences in ground test and flight environments, thrusters used in deep space may be subjected to unusual conditions (the dust environment around small bodies, for instance). The classification process should be designed to help identify the subset of life-limiting wearout failure modes that are the focus of the life assessment.

F. The 12 Step Program for Managing Wearout Failures

The process for managing wearout failures is summarized in Fig. 11. The critical first step is to identify the relevant failure modes, each of which must be dealt with in the following steps. The focus of steps 2-7 is to understand the physics of failure for each mode. Ideally this results in sufficient insight to eliminate the failure mode by design. If not, a deterministic calculation of the time-to-failure (step 8) may yield a time so far beyond the lifetime requirement that the failure mode is not credible, even with conservative estimates of the uncertainty or variability in the failure process. For the remaining, life-limiting failure modes a detailed assessment of the uncertainty and variability is required to determine the failure risk, which is the objective of the final four steps.

IV. Current NASA Practices for Deep Space Missions

A. The Dawn Mission and Ion Thruster Lifetime

Because the Dawn lifetime requirements were very close to what had been demonstrated in test, it was critically important to assess the risk of wearout failures for the NSTAR ion thruster as implemented on Dawn. This assessment made use of over 58,000 hours of ground and flight test experience with the NSTAR thruster design including the 30,352-hour life test of the DS1 flight-spare thruster and 16,265 hours of in-flight operation of on DS1. This extensive test experience along with the substantial body of ion thruster life test information in the literature dating back to the early 1960s was used to identify all of the key

The full 12-step program:

1. Identify the relevant failure modes
2. Identify the fundamental physical mechanism for the failure process
3. Define drivers of the failure mode
4. Develop a model of the failure process
5. Validate key model components experimentally
6. Characterize drivers in the thruster
 - a. Define model input parameters
 - b. Understand margins—sensitivity to variations in thruster operating conditions
7. Determine the effects of environment (ground/space, component/thruster, etc.)
8. Develop a deterministic failure prediction
9. Quantify intrinsic variability and uncertainties in model input parameters
10. Determine model uncertainties/limits of applicability
11. Perform probabilistic risk analysis if necessary
12. Quantify life margin

Offramps:

Modify design to eliminate failure mode (ideal)

If time-to-failure is far beyond mission requirement and uncertainties are small, this may be sufficient

Full process required for dominant failure modes with significant uncertainties

Figure 11. A prescription for determining margin by analysis.

wearout failure modes with high confidence. The first wearout failure mode for the NSTAR ion thruster at full power was identified during the ELT. In January 2003, after 25,700 hours of operation, and after processing 211 kg of xenon, the DS1 flight-spare thruster could no longer be operated at full power due to electron-backstreaming.⁵ The thruster had been tested to failure as requested by the review board three years earlier. The thruster, however, was still fully functional at lower throttle levels and the test was continued for another 5,000 hours before being terminated for non-technical reasons. This test provided a wealth of data on the engine failure modes and how they behaved as the engine approached failure. However, it was very difficult to keep the test funded for the five years required to accumulate this much operating time. This single wear test had five different funding sources over this time.

To assess the wearout failure risk for Dawn all of the key failure modes were addressed. Conservative assessments or deterministic models were used to conclude that there were significant margins for all of the failure modes except for electron-backstreaming due to accelerator grid erosion. For this failure mode a detailed semi-empirical assessment based on the results from the ELT was used in a probabilistic failure analysis (PFA) to quantify the risk for the worst case use of the thrusters (i.e., where the entire mission is performed with just two thrusters).²⁴ The results of this analysis are similar to those for full power operation shown in Fig. 8. This analysis showed that the probability of a wearout failure due to erosion of the accelerator grid resulting in electron-backstreaming was less than one percent if the entire Dawn mission is performed with just two thrusters, and the two thrusters are the worst two based on the thruster acceptance test data. The PFA, in this case, was used to make a convincing case that the risk for reducing the margin relative to the single long-duration ELT was acceptable.

All three thrusters have operated flawlessly and there has been no evidence of engine degradation. The Dawn development and flight experience demonstrates that it can be difficult to maintain programmatic support for very long wear tests and also difficult to maintain test margins as a project evolves. However, the focus on testing to understand the dominant failure modes coupled with modeling provided sufficient information for the project to make informed decisions.

B. The Proposed Life Qualification Standard and The JPL Design Principles

The lessons learned from Dawn and other development programs were codified in a proposed standard developed for the American Institute of Aeronautics and Astronautics (AIAA) to help guide the electric propulsion community in the life qualification process.^{29,30} The standard was not ultimately adopted by the AIAA, but has been provided in the Announcements of Opportunity for NASA's Discovery and New Frontiers competed missions as guidance for proposers.

The requirements developed for the standard include the following:

D. GENERAL REQUIREMENTS

A thruster shall have a service life of 1.5 times the worst-case planned mission usage. The service life shall be validated through a combination of testing and analysis, demonstrating a non-failure probability due to wearout of greater than 90%, including modeling uncertainties and assuming the thruster is operated for 50% more time at every throttle level over the expected mission profile. Throttle points may be grouped provided the worst case operating point is used for the group. Lifetime qualification can be completed by test alone, eliminating the analytical model requirement 5.4, provided a sufficient number of tests are performed to establish the location of the failure distribution.

E. DETAILED REQUIREMENTS

1. Failure Mode Identification and Understanding

The behavior on approach to failure shall be known for all of the significant failure modes over the applicable throttle range.

2. Minimum Test Experience

A test of a Development-Model fidelity thruster, or better, shall be executed in a relevant environment over the intended throttle range under nominal operating conditions and shall demonstrate an equivalent or greater accumulated damage, with emphasis on the progression of the first failure mode, than any individual thruster is anticipated to be subjected to for the proposed mission. Thruster level testing shall demonstrate a total impulse greater than or equal to 100% of the worst-case planned thruster usage. Cycle testing shall be completed at the thruster or component level with a minimum of 150% of the worst-case expected number of cycles demonstrated by test.

3. Engineering Model Hardware Tests

Extended-duration testing with an Engineering Model fidelity thruster or better must be performed to verify that the flight thruster life characteristics are consistent with expectations and to identify any significant failure modes that are sensitive to fabrication processes. Vibration environmental testing shall occur prior to the Engineering Model hardware testing.

4. Analytical Model Requirements

A favorable external review, as defined in NASA-STD-7009, is required for each model of a significant failure mode. These models shall be used to perform a probabilistic risk assessment according to NASA's Procedural Requirement NPR 8705.5.

The standard specifies that a margin of at least 50% be demonstrated by analysis and test for thruster operating time at each throttle level, although assessment at the worst-case operating points is permitted if they can be identified. As noted above, a margin of 50% only protects against failure modes with narrow failure probability distributions (high values of β). However, the purpose of modeling in part is to understand how much margin is required for a given failure process and the analysis may show that more than 50% is needed for low failure risk. Allowing the primary wear test be conducted on a development model thruster (section D.2) reflects the reality that a sufficiently long wear test must often be started early in the development. The risk, of course, is that subsequent design changes will render this test unrepresentative of the flight hardware, which is why section D.3. requires verification that the engineering model hardware behaves similarly. The minimum test experience must demonstrate both 100% of the required total impulse and accumulated damage equal to what is expected in the mission. As noted above, the specified percentage is arbitrary, but this is considered the minimum required to gain confidence that all potential failure modes have been identified and the evolution of the wear is understood. Finally, an external review of the modeling is required, which is consistent with recent NASA requirements for verification and validation of models and

simulations used in decision-making.³¹

An abbreviated form of the specification has also been incorporated in JPL's Design Principles.³² This guideline includes the same margin and test time as the more detailed proposed standard:

4.7.3.4 Electric thruster life margins—Electric thrusters shall demonstrate by life test a total impulse capability of 100% of the planned worst-case mission usage, and by test or analysis, a margin of at least 33% (factor of 1.5 times the required life). Electric thrusters shall demonstrate by test greater than 33% margin beyond the planned worst-case number of deep thermal cycles (factor of 1.5 times the required number of cycles).

V. Implementation in the Advanced Electric Propulsion System (AEPS) Project

A. Identification and Classification of Potential Failure Processes

In the SEP TDM project, failure modes are being identified and classified through the FMEA process. In addition to failures that have been observed in Hall thruster components or other similar components, we identified processes that could lead to loss or degradation of the function associated with each component or interface. For each major subsystem (cathode, discharge chamber, magnetics, thermal and mounting) component failures were evaluated in terms of lost function, cause, effects and potential mitigation. The failures were categorized according to the scheme shown in Fig. 10 (e.g. design flaws, wearout, material flaws, workmanship errors). Risks were then assigned by assessing severity, likelihood and detectability for each mechanism. Each failure cause was evaluated for when it would likely be detected, prevented, or retired (e.g. design analysis, assembly inspection, qualification test, acceptance test, wear test). Figure 12 shows the number of potential failure modes by category.

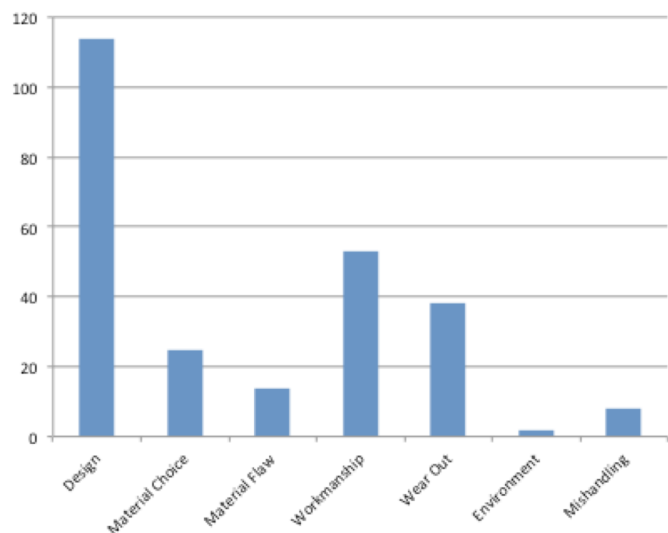


Figure 12. Potential failure modes for the AEPS 12.5 kW Hall thruster grouped by type.

The objective was to try and capture every conceivable path to failure, so many of these failure modes are not credible (such as structural failure of the back pole during launch) and will be screened out in design analysis or inspections. The plan for addressing each of these potential failure modes is summarized in Fig. 13. The risk ratings and detectability assessment were used to identify the critical subset of these potential processes that are likely to be the life-limiters. These include:

- Pole erosion
- Cathode emitter erosion or activator depletion
- Heater failures due to time-at-temperature or thermal cycling
- Electromagnet failures due to thermal cycling
- Discharge channel cracking
- Ground test failures due to shorts from spalling deposits, performance changes from carbon deposition, or change in thermal properties due to deposition or erosion
- Keeper and cathode orifice plate erosion

- Keeper-cathode shorts

The FMEA is being updated as new information becomes available and is being used as a tool to develop inspection, test, and analysis plans.

B. Three Examples of Hall Thruster Wearout Failure Modes

The SEP TDM program is following the requirements outlined above for the life qualification of the AEPS thruster. Three of the dominant failure modes identified in the FMEA process provide examples of the range of approaches we are employing to satisfy these requirements. A potential failure mode for the cathode assembly is a shorted or open condition in the cathode heater. In this case it is feasible to test multiple units at the component level. Previous test experience indicates that the failure probability distribution is sufficiently narrow that a more conventional approach based on statistical analysis of data from cycled heater tests will demonstrate high reliability. However, other focused tests and analytical modeling of the dominant heater failure processes will be used to supplement life demonstration in cycled tests.

Loss of electron emission capability due to barium depletion is considered to be the dominant failure mode for the emitter in the hollow cathode assembly. The models of barium depletion are relatively mature and the drivers are well-understood from ion engine experience.^{33,34} The effect of time-varying currents experienced by the cathode in Hall thrusters is currently being investigated, but the expectation is that analysis and test will show that the time-to-failure for this mechanism is sufficiently far beyond the lifetime requirement that a full probabilistic risk assessment is not required.

Erosion of the inner front pole, which is currently considered to be the first failure mode for the thruster, is not as well-understood. The carbon pole cover is an engineering solution that will provide adequate life based on measured erosion rates. The models of the erosion process are becoming more mature, but the expectation is that the predicted lifetime will be comparable to the required life, so a full probabilistic risk assessment may be required. Because this failure mechanism is more complex it is discussed in more detail in the next section as an example of the full 12 step process.

C. Hall Thruster Pole Erosion As a Detailed Example of the Life Qualification Process

Erosion of the ceramic discharge channel was previously considered the main life-limiting process in Hall thrusters. Channel erosion has been eliminated as a credible failure mode in the AEPS thruster through the use of magnetic shielding.³⁵⁻³⁸ Magnetic shielding involves a carefully engineered magnetic field topology and discharge chamber configuration that prevents bombardment of the discharge channel wall by high energy ions. This is the first thruster designed from the outset to incorporate magnetic shielding and a number of experiments and simulations have verified that discharge channel erosion has been eliminated.^{39,40} Erosion of the inner front pole appears to be a consequence of magnetic shielding, which moves the acceleration zone further downstream and produces potential gradients at the edge of the beam that result in greater divergence of high energy ions. This is now thought to be the life-limiter for shielded Hall thrusters, although the rates of pole erosion are much lower than the rates of channel erosion in unshielded thrusters,⁴¹ resulting in much longer lifetimes.

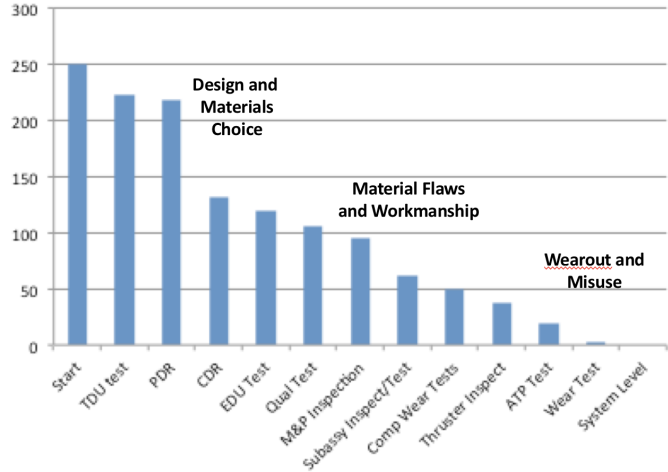


Figure 13. Plan for retiring potential failure modes for the AEPS 12.5 kW Hall thruster. The bar height represents the number of potential failure modes remaining after each event.

The SEP TDM project is using the 12-step program outlined in Section F to assess the failure risk associated with pole erosion. Each of the steps is discussed in detail below as an example of this process.

1. Step 1: Identify the Relevant Failure Modes

Pole erosion was first observed in a 150 hour wear test of the H6MS at 300 V (2000 s Isp) and 6 kW and was further characterized in a series of short duration wear tests, including a 100 hour test at 800 V (3000 s Isp) and 9kW.²⁶ A second 150 hour wear test at 300 V and 6 kW incorporated a sputter-resistant graphite pole cover instrumented with radial strips of molybdenum, which served as masks for the graphite cover and were themselves masked so the wear rate could be measured on them as well.²⁷ The masks provided uneroded reference surfaces that could be compared to the eroded surfaces using an optical profilometer. These measurements yielded graphite erosion rates of 25-71 $\mu\text{m}/\text{hr}$ and molybdenum wear rates of 120-270 $\mu\text{m}/\text{hr}$. The erosion profile peaked at inner and outer edges of the face of the graphite cover.

A subsequent 1722 hour test of TDU-1 was conducted to characterize wear rates in the HERMeS thruster.⁴² The test consisted of four segments with several different configurations. The erosion profiles were similar to those observed on the H6MS pole cover, with rates on graphite that ranged from 10-45 $\mu\text{m}/\text{hr}$ and rates on molybdenum of 100-600 $\mu\text{m}/\text{hr}$. A systematic variation in the erosion rates for both materials by up to a factor of two between various test segments was noted. These initial observations indicated that pole erosion was an important new wear process with rates that could threaten the function of the magnetic circuit on time scales similar to required lifetimes. The apparent variability of the erosion rate between test segments was also a concern because of its implications for the width of the failure distribution.

2. Step 2: Identify the Fundamental Physical Mechanism for the Wearout Process

The surface texturing noted in early tests was clearly due to sputter erosion from high energy ions. Subsequent modeling and analysis have shown that ions born at high potentials near the beam edge can impact the pole, contributing to erosion. There is also experimental evidence that the cathode plume may be a source of high energy ions that could contribute to pole erosion; however, the physical mechanisms for ion acceleration from the beam edge at low voltages (300–400 V) and from the cathode plume and are not currently understood. Key tests to illuminate the mechanisms include time-averaged and time-resolved Laser-Induced Fluorescence (LIF) measurements of ion velocities in the main plume, beam edge, and cathode plume of the thruster, as well as ion energy measurements in cathode components and plasma density and potential measurements in the cathode plume. Simulation activities include refined modeling of the structure of the electric potential at beam edge, motion of the acceleration zone, and cathode plume modeling to determine ion fluxes and energies.

3. Step 3: Define Drivers of the Failure Mode

Experiments and modeling have shown that the primary drivers are discharge current and voltage, amplitude of current oscillations, magnetic field magnitude, and the location and movement of the acceleration zone. To determine the primary drivers, the erosion characteristics of a molybdenum cover on the inner front pole of the TDU 2 Hall thruster were measured over a wide range of operating conditions.⁴³ The operating points included the nominal 300 - 600 V conditions on a constant 20.8 A throttle curve, as well as conditions at other currents spanning the throttling envelope and with varying magnetic field strength, facility pressure, and discharge voltage oscillation amplitude. Molybdenum was used to accelerate the wear rate, and this in combination with a very sensitive, radioactive tracer-based erosion diagnostic allowed test durations of 6 to 14 hours. Surprisingly, the results show that the highest wear rates occur at the lowest voltages and currents, as shown in Fig. 14. The wear rates were insensitive to discharge voltage ripple, but increased monotonically with magnetic field strength, particularly near the inner radius of the pole cover. These trends were subsequently confirmed in longer duration tests with a graphite cover.⁴⁴

The erosion measurements at a number of operating points indicated high erosion rates at the inner face and the inner diameter edge of the pole cover, which suggested that the cathode could be an additional source of

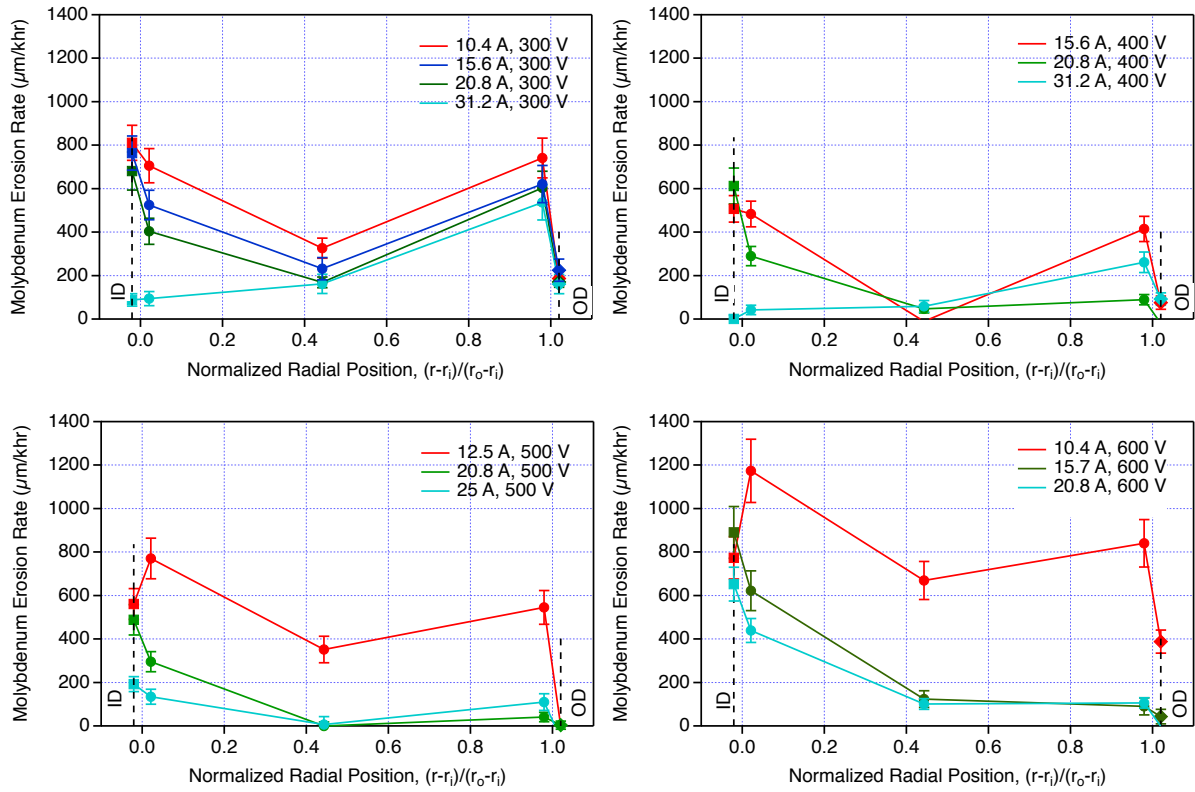


Figure 14. Erosion rates measured at a range of discharge currents for discharge voltages of 300–600 V.

high energy ions. To test for this, a separate cathode experiment was performed and high energy ions were indeed observed at the conditions with high wear rates at these locations, as shown in Fig. 15. Additional measurements to further characterize this source of high energy ions are currently underway.

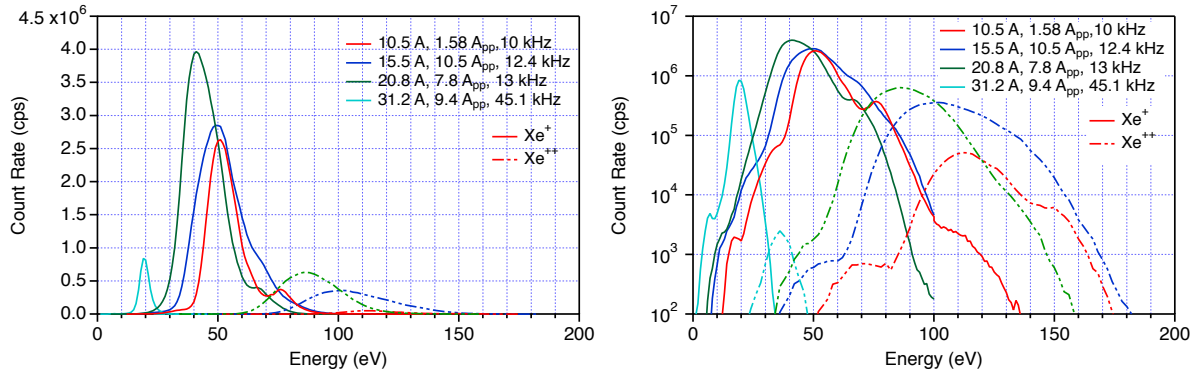


Figure 15. Ion energy distributions measured in cathode experiments simulating thruster operation at 300 V with varying currents, displayed on linear and semilog plots.

4. Step 4: Develop a Model of the Failure Process

The Hall thruster simulation code Hall2De is being used to model pole erosion. Hall2De was originally developed at JPL to study discharge channel erosion,^{35,36} and was not initially well-suited for modeling pole erosion. However, a number of advances implemented over the last three years^{40,41,45,46} and code benchmarking with laser induced fluorescence (LIF) measurements of the acceleration zone location⁴⁷ have made it a much more powerful tool for this application. Figure 16 shows the basic structure of the model.

Hall2De is a 2D axisymmetric code that employs a quadrilateral-based computational mesh aligned with the magnetic field lines over a domain that includes the discharge channel and a region downstream that is several times the length of the channel in the axial and radial directions. Neutral particles are modeled using a free-molecular flow approach and continuity and momentum equations are solved for multiple charged species populations. Electrons are also modeled as a fluid with the inertia term neglected, so it takes the form of Ohm's law which is solved in the directions parallel and perpendicular to the magnetic field to obtain the plasma potential. An electron energy equation is solved for the electron temperature. Ionization, charge exchange, and elastic collisions between the various species are included. The ion fluxes and energies are used with measured sputter yields to determine the erosion rates in post-processing. Additional post-processing modules yield the thruster performance parameters and heat fluxes to the thruster surfaces.

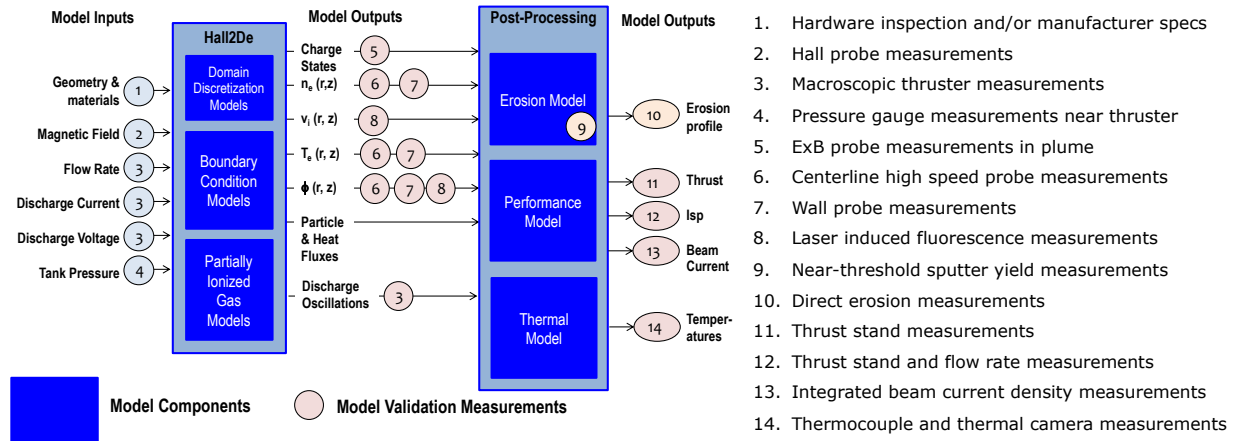


Figure 16. Hall2De model structure and validation approach.

Several model improvements, some motivated by the pole erosion problem, have proved to be essential in getting partial agreement with the data obtained to date. In the original code the ions were treated as a single fluid, which yielded accurate results for the beam ions responsible for channel erosion. However, in most cases the beam ions created upstream of the acceleration zone are not responsible for much pole erosion because their trajectories do not intersect the pole face. There are three other ion populations which do not easily thermalize with the beam ions because of their short residence time, so they are not properly represented by the beam ion fluid. These populations are (1) low energy ions created downstream of the inner pole face between the beam and the cathode plume by charge exchange or cathode plasma electron impact, (2) thruster plume ions born in the acceleration zone or further downstream in the plume which have energies lower than the beam ions, and (3) cathode plume ions. Hall2De has been updated to treat these ion populations as separate fluids or model them as discrete macroparticles using Particle-in-Cell (PIC) methods.^{40,41,45} LIF measurements of ion velocities near the inner pole and measurements of the plasma potential have shown that the ions created locally near the pole do not have sufficient energy to cause significant sputtering.⁴⁶ However, these measurements and modeling showed that the potential distribution at the beam edge creates a pathway for ions generated in the thruster plume to reach the inner pole and they have been identified as a major contributor to erosion in some cases.^{40,46} The codes do not currently reproduce the high energy ion populations generated in the cathode plume, which is currently modeled as a separate fluid.

A second improvement is in the way the code treats regions with low plasma density, where the Debye length can approach or exceed the cell size in the mesh. An algorithm which provides an improved potential calculation using the calculated space charge and Poisson's equation led to ion densities between the beam and the cathode that better matched experimental data, potential distributions at the beam edge that allow thruster plume ions to turn toward the pole, and more realistic sheath potentials along the pole face.^{40,45}

Several updates to the code geometry played a role in pole erosion simulations.^{40,45} The details of the geometry between the discharge chamber wall at the channel exit and the outer edge of the inner front pole have an important effect on the local potentials. A higher fidelity boundary model was implemented to better resolve this location. The size of the overall simulation domain was also increased to more accurately

capture the interaction between the cathode and thruster plumes. This turned out to impact thruster near-field plume potentials, which control the energy of the ions born in the plume. A related code upgrade was an improved model of anomalous transport in the cathode plume, which was essential to match potential gradients measured downstream of the cathode.⁴⁸

5. Step 5: Validate Key Model Components Experimentally

The circles and ellipses in Fig. 16 represent points where input or output parameters are being measured and the numbers identify the type of measurement. These measurements are designed to document the input parameter pedigree, validate key model subelements with intermediate parameters such as ion velocities and plasma densities, and provide erosion data to compare with the end result of the modeling. Many of the Hall2De model assumptions and plasma models have been validated with data from multiple thrusters over the last 8 years.^{35,36} Specific validation activities for pole erosion modeling are focused on the location and motion of the acceleration zone and the actual erosion rates.

Laser induced fluorescence measurements yield the ion velocities, from which the potential distribution in the acceleration zone can be inferred. These measurements in the H6MS and TDU-2 thrusters have been instrumental in benchmarking the acceleration zone location for modeling. In the code, the location of the potential gradient that accelerates the ions is determined by an empirical model of the anomalous collision frequency. This was informed previously by probe measurements of the potential and electron temperature in the thruster discharge, but these were found to perturb the location of the acceleration zone.⁴⁹ An LIF system was then built to make non-intrusive measurements of the ion velocity, from which the potential distribution could be inferred.⁴⁷ These data have been used to improve the specification of the anomalous collision frequency profile in the code, reducing a major source of uncertainty in the code results. Figure 17 demonstrates excellent agreement between the measured and calculated ion velocities along the centerline of the channel with the updated anomalous collision frequency profile.

In addition, the LIF data from these time-averaged measurements and from previous time-resolved LIF measurements suggest that the acceleration zone moves during thruster breathing mode oscillations. This was simulated in the code by specifying a time-dependent spatial profile of the anomalous collision frequency, allowing periodic motion of the acceleration zone with an amplitude and frequency specified by measurements of the discharge current oscillations from thruster tests.⁴⁰ This appears to be a primary driver of pole erosion for certain operating conditions. Time-resolved LIF measurements will be made in the next few months to verify the amplitude and frequency of the acceleration zone movement.

The radioactive tracer and profilometer measurements of pole cover wear have provided data at a number of operating conditions to help validate the Hall2De results. Figure 18 shows the maximum wear after 34,500 hours (1.5 times the lifetime requirement) predicted by Hall2De and inferred from erosion measurements for the four nominal AEPS thruster operating points.⁴⁰ The Hall2De results for the 600 V, 20.8 A condition agree reasonably well with measured wear rates.⁴⁰ The data are generally higher than the prediction by 50-100%, and radial profiles of erosion rates show that the worst agreement is at the outer radius of the pole face. The predicted profile drops monotonically with radius, whereas the SLA and profilometer measurements generally show flat or increasing rates at the outer radius. Initial models of wear underpredicted the rates drastically,^{41,45} and the recent success in modeling this condition is primarily due to three of the code improvements discussed above. The addition of the space charge algorithm increased the predicted wear by about a factor of two. The improved

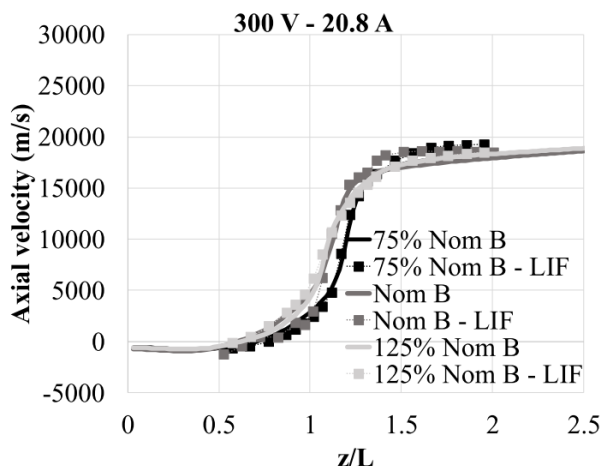


Figure 17. Comparison of centerline ion velocity measured with LIF (points) and calculated by Hall2De (lines).⁴⁰

boundary geometry between the channel exit and the pole edge increased the predicted wear rate by a factor of about three to five. Finally, including motion of the acceleration zone led to an order of magnitude wear rate increase. These results highlight the importance of the local potential in deflecting plume ions toward the pole and the location of the acceleration zone. Displacement of the acceleration downstream results in higher potentials downstream of the channel exit and gives more high energy ions a line of sight to the pole face. The discrepancy at the outer radius of the pole suggests that further improvements in the local potential model may be required.

The radioactive tracer erosion data indicated that the 300 V, 20.8 A condition is the worst case of the nominal throttle points. This finding motivated the subsequent short duration wear tests using TDUs 1 and 3, which confirmed the result. In this case the model underpredicts the erosion rate by a factor of five to ten.⁴⁰ The LIF data indicate that the location of the potential profile is not very different at 300 V compared to the mean position at 600 V, but there was no evidence of significant motion.⁴⁷ The discharge current oscillation amplitude was much smaller than at the 600 V case, so the displacement of the acceleration zone that was crucial to capturing the erosion behavior at 600 V is absent at 300 V. The mechanism for the high erosion rate at 300 V is still not clear. LIF measurements of ion velocities near the beam edge indicate greater beam divergence than predicted by the code.⁴⁷ This effect is difficult to reproduce in Hall2De and suggests that code does not currently incorporate the physics required to correctly model the potential gradient along the magnetic field lines.⁴⁰ There is either an additional force that is not included or the model of electron transport along the magnetic field is not quite accurate, leading to lower beam divergence. The divergence of the beam ions is not likely to be the cause of the pole erosion at this condition because their trajectories will not intercept the pole. The beam edge potential that causes divergence of the beam ions may also more significantly influence the trajectories of ions generated in the plume which can strike the pole, however.

Additional model validation efforts include ongoing LIF measurements of the ion flow field at the beam edge and in the cathode plume, more detailed measurements of the acceleration zone movement, ongoing cathode ion energy measurements with time-varying currents, an ongoing wear test of TDU-3, a longer duration test of the EDU thruster, and the final wear test of the qualification thruster. Model validation will continue throughout the duration of the AEPS project.

6. Step 6: Characterize Drivers in the Thruster

The primary drivers are listed in Step 3. Many of these have been characterized in thruster tests. For example, the discharge current and voltage oscillations measured over the throttling envelope with TDU-2 are summarized in Fig. 19. The vertical bars in the plot represent the peak-to-peak amplitude of the current oscillations and the horizontal bars are the corresponding peak-to-peak voltage oscillation amplitude. The symbol size is proportional to the frequency of the oscillations, as shown in the legend in the upper right. The symbol colors correspond to particular mean current levels and in some cases the data points have been shifted slightly in voltage to more easily distinguish the vertical bars. The data show that the current oscillation amplitude increases with discharge voltage and is particularly low for the 300 V cases. Two oscillatory modes are apparent—a low frequency mode at lower currents and voltages and a higher frequency mode that occurs as voltage and current are increased. Current experiments are focused on characterization of the acceleration zone motion and the cathode plasma conditions.

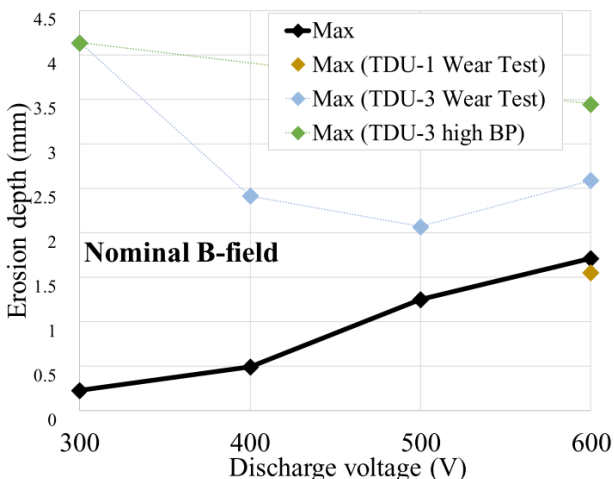


Figure 18. Comparison of the maximum measured erosion depth (colored lines and points) and wear predicted by Hall2De (black line) after 34,500 hours of operation as a function of discharge voltage.⁴⁰

7. Step 7: Determine the Effects of the Environment

The main concern with pole erosion is the effect of the ambient pressure in ground test facilities. Some variation in erosion rate with different facility pressures has been observed. For example, the radioactive tracer measurements showed that increasing the chamber pressure from 15 to 27 μ Torr had no impact on erosion in the middle or outer face of the molybdenum cover, but decreased the erosion rate at the inner diameter edge and inner face by about a factor of two.⁴³ A similar reduction was observed in graphite covers, but the same tests showed an increase in rate for molybdenum.⁴⁴ The differences are on the order of variability in the rates measured at constant pressure, so it is not clear if they reflect a real effect of pressure. The LIF measurements showed that a factor of two increase in facility pressure resulted in movement of the acceleration zone upstream by about 5% of the channel length. Incorporating this in the Hall2De simulation led to a drop in the erosion rate of approximately 20%. This is an ongoing area of research, and additional LIF measurements and modeling are underway to ensure that the model accurately captures erosion characteristics of the space environment.

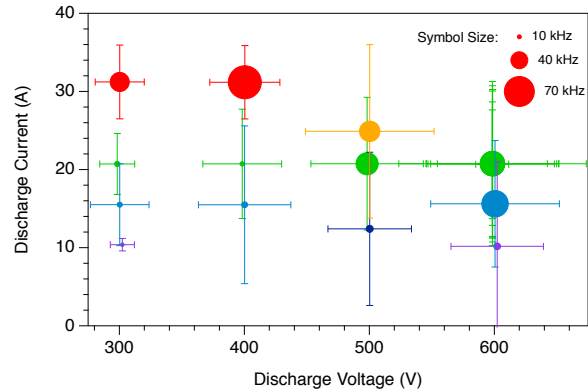


Figure 19. Discharge current and voltage oscillation amplitude and frequency for the test conditions.

8. Step 8: Develop a Deterministic Failure Prediction

Failure in this case is defined as the point in time when the graphite pole cover is penetrated by sputter erosion. This is quite conservative as far as the magnetic circuit function is concerned, because it would be unaffected by loss of the cover. In fact, parametric magnetic field simulations show that the inner front pole can suffer significant erosion before the field strength or shape in the channel is affected. However, we were concerned that through could liberate pieces of the cover which could short the cathode keeper-to-body gap, for instance. The current nominal wear prediction plotted in Fig. 18 shows adequate margin against this failure mode at 600 V. The model cannot yet reproduce the measured erosion for the lower voltage operating points, so no assessment of failure risk can be made at this point based on the model. The nominal deterministic life prediction will be updated periodically as the models mature. We are currently defining the worst case model input parameters to define the worst case life. The expectation is that this result will not have adequate margin and the uncertainties in the primary drivers will have to be reduced by additional analysis and testing.

9. Step 9: Quantify Intrinsic Variability and Uncertainties in Model Input Parameters

Planned experiments and analyses are designed to characterize the variability in the key input parameters. These include measurements of the sensitivity of acceleration zone motion to thruster and environmental parameters using time-resolved LIF, characterization of the variability of discharge current and voltage to operating conditions and from thruster-to-thruster, variations in the fluxes and energies of ions that impact the pole, and uncertainty in sputter yields at relevant energies. The erosion data show variations in rates of up to a factor of two at otherwise identical operating conditions or test segments. This variation may be due to experimental errors or to intrinsic variability in the erosion drivers.

10. Step 10: Determine Model Uncertainties/Limits of Applicability

Initial steps have been taken in benchmarking model accuracy with wear test data, as described above. Ultimately this will be combined with an assessment of the range of applicability for each code module based

on the underlying physics and approximations to define the uncertainty in the model formulation (which is distinguished from uncertainty in model inputs).

11. Step 11: Develop Probabilistic Framework for Risk Analysis

If the uncertainties in model inputs and potential model errors result in large uncertainties in the predicted lifetime compared to the required life (in practical terms, if the predicted lifetime is not much, much greater than the life requirement), a full probabilistic risk assessment will be performed. The first step in this process is to define probability distributions with capture the uncertainty and variability in the input parameters. Second, a Monte Carlo simulation framework will be developed in which model inputs are drawn randomly from the input parameter distributions and used to predict the time to failure. It will not be feasible to embed the Hall2De simulations in the Monte Carlo analysis (which will require tens of thousands of simulations), so a response surface will be constructed for a smaller number of simulations that span the range of input parameters. In the Monte Carlo simulation, model output values will be interpolated from the response surface for the input parameters. The framework will have to include the capability to calculate the wear at each throttle level for specific mission profiles.

12. Step 12: Quantify Life Margin

The results of the Monte Carlo simulation will be used to infer the failure distribution, from which the reliability for a given mission duration can be calculated. Additional modeling and tests may be necessary to reduce the uncertainty of the main drivers if it results in unacceptable failure risk. This probabilistic assessment will be updated as new data are obtained from ongoing wear tests and as candidate mission throttle profiles become more well-defined.

VI. Summary and Conclusions

Hall thrusters offer great promise for human and robotic exploration missions because of their performance, but qualifying them for the long burn times required in low thrust missions is challenging. The traditional life qualification method, a single wear test of 1.5 times the required mission life, is not sufficient to demonstrate low failure risk. Longer duration testing or testing more units is not feasible given typical mission development schedules.

The SEP TDM project is following an approach outlined in the proposed NASA life qualification standard³⁰ and in the JPL Design Principles³² to qualify the 12.5 kW AEPS Hall thruster. Thruster wear testing is not used to directly assess reliability, but to help identify the dominant wearout failure modes, guide and validate physics-based models, and characterize failure mode drivers. Modeling and simulations are then used to assess the failure risk. This approach has been successfully applied to the ion propulsion system on the Dawn spacecraft.

A Failure Modes and Effects Analysis is being used to help identify and document potential failure modes for the engine. These have been classified by cause, and the life qualification plan shows that the vast majority of these can be eliminated during development, qualification, and acceptance testing by conventional conservative design, margin testing, inspections, and standard quality assurance controls. A small subset of the identified failure mechanisms are wearout modes that have to be managed primarily by analysis. Many of these can be shown to have such large margins that detailed analysis is unnecessary. For a few, detailed probabilistic failure analysis is likely to be required.

Erosion of inner front pole cover and ultimately the pole itself is currently considered the first failure mode for the thruster. Physics-based models of the sputter erosion due to the discharge and cathode plasmas are being developed and validated with measurements of plasma properties and wear rates. The models currently reproduce the erosion observed at the 600 V to within about a factor of two, but significantly underpredict the erosion at 300 V. The current focus of the life qualification effort is improving the fidelity of the models, particularly for low voltage operation. A ongoing wear test which will accumulate up to 15%

of the required lifetime and a planned test of 100% of the required life will provide the final validation data for the modeling.

Most of the required thruster capabilities, although difficult to achieve, can be demonstrated in relatively short duration tests or using mature analysis tools. Lifetime is uniquely difficult to validate, although one of the most critical parameters for a system that will be attached to a multi-billion dollar spacecraft on which astronauts rely. Success requires a commitment to an ambitious testing program and diligence in developing and validating the required models. With this approach, however, a project can demonstrate low risk of failure with high confidence.

VII. Acknowledgments

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